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13. SUPPLEMENTARY NOTES

14. ABSTRACT
The research performed under this grant has been on the high-temperature vibration damping of materials related to use in gas turbines. The research has led to three major accomplishments. The first was the design and construction of the only instrument in the US capable of measuring the flexural damping characteristics of materials up to temperatures of 1150oC in air. This instrument was used to evaluate the damping properties of materials and coatings currently being used, as well as those being contemplated for future use, in the hot, turbine sections of gas turbines in order to establish a data base of high-temperature damping properties and supplied to GE and Pratt & Whitney. The third accomplishment was the identification that the major damping mechanism in oxide thermal barrier coatings is defect hopping in response to the alternating strain reversals generated by flexural vibration and the development of a model for predicting alternative oxide coating materials with both superior damping and thermal conductivity characteristics.

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FINAL REPORT

to

THE OFFICE OF NAVAL RESEARCH

Contract N00014-04-1-0053
November 2006 to October 2009

COATINGS FOR HIGH-TEMPERATURE VIBRATION DAMPING OF TURBINES

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EXECUTIVE SUMMARY

Vibration can induce fatigue damage in engine components, especially rotating components, and so a variety of approaches have been traditionally been employed to dampen vibrations in gas turbine engines. These include the use of mechanical dampers, braces and discrete damping pads. In this research program our focus has been on exploring whether it is possible to develop coatings that incorporate vibration damping as well as having the other attributes for which the coating material was originally selected. The idea being to develop and select a multi-functional coating material that provides vibrational damping as well as, for instance, oxidation or thermal protection.

The research program had two related technical objectives. One was to evaluate the damping properties of materials and coatings being used, or contemplated for use, in gas turbine engines to establish a data-base of damping properties up to 1200°C. The other was to identify new materials with potential for conferring, as coatings, damping capacity to blades to decrease the vibration-induced strains. As no equipment existed in the US with the capability of measuring damping up to these high temperatures, we also had to develop a capability to quantify vibration damping in air. The research performed and results obtained are described in the reports listed at the end of this report which have been previously provided to the contract monitor and published in the open literature.

The instrument we designed and constructed is described in Report #1 with improvements for operation up to 1200°C included in Report #2. The instrument was designed to make measurements under flexural vibration conditions and measurements at kHz frequencies were emphasized since these correspond to flexural vibrations induced in blades as a result of buffeting as they successfully pass behind vanes and into the turbine gas flow. Discussions with colleagues at the major engine companies had identified this vibrational regime to be of most interest to them. The instrument is based on setting flexural beams of selected materials into resonant vibration using a white-noise exciter and measuring *in-situ* and without any contact the displacements of the beam as a

function of frequency. The displacements were measured using a laser vibrometer outside of the furnace with the beam inside the furnace. In addition to quantifying the damping characteristics, the instrument also provides information on the elastic modulus of the material from the resonance frequencies.

Data on the damping capacity of a wide variety of metallic alloys and coatings, as well as elastic modulus data, as a function of temperature was obtained over the course of the program. This activity was primarily on materials currently used in aero-turbines made by both GE and Pratt-Whitney and used by the Navy. The principal results are described in reports #1 and #2 and on materials supplied by those companies as well as Howmet Research Corporation. In addition to obtaining new data, several new insights on the damping behavior were obtained. Principal amongst these were that: (i) distinct and measurable damping is provided by both the thin bond-coat and thermal barrier coating (TBC) in TBC coated superalloy system, (ii) the damping from each component in a TBC system is additive in the sense that at each temperature the damping capacity is the sum of the damping capacities of the superalloy, the bond-coat and the TBC itself, and (iii) damping from EB-PVD deposited TBCs and platinum-modified nickel aluminide bond-coats occur at the same temperatures as the occurs in their bulk counterparts.

Once the characterization of existing materials had been performed, the majority of the program was devoted to identifying damping mechanisms appropriate to high temperatures and prospective oxides and bond-coat compositions that could exhibit favorable damping characteristics.

Based on work in the literature as well as ourselves, it was concluded that the mechanism responsible for the damping we observed in the yttrium stabilized zirconia TBCs is due to defect hopping in response to the alternating vibrational strains in the coating. This is a mechanism that can occur in defective oxides and is associated with point defects. Using this as a guide, we investigated the properties of several defective and refractory oxides. Three oxides with a high concentration of oxygen vacancies,

yttrium stabilized zirconia, yttrium zirconate ("delta phase") and gadolinium zirconate ("pyrochlore") exhibited pronounced damping at high temperatures. (Report #3). These oxides also have the potential to also be used for thermal protection because of their unusually low thermal conductivity at high temperatures.

At the present time, it is not possible to predict *a-priori* the peak damping temperatures for point defect damping of different compounds. However, some guidance comes from the analysis of defect relaxation originally presented by Wachtman. He considered the rearrangement of point defects that could adopt a variety of equivalent crystallographic sites and how an alternating field affects the number on each site as they respond to the field. In effect, the point defect configurations represent different defect dipoles and in response to the applied field direction, the point dipoles reorient by the point defects diffusing to equivalent configurations but with lower energy. The energy dissipation is then controlled by the vibrational frequency applied and the diffusional jump rate. The latter, which depends on the energy barrier between the different defect sites, is related to temperature by an activation energy, E_i, similar to that for diffusion. The relationship that Wachtman derives between the damping factor, Q^{-1}, temperature, T, frequency, ω, and relaxation time, τ, can be expressed as

$$Q^{-1} = \frac{A\,Y\,N}{k_B T}\,\mathrm{sech}[\ln(\omega\,\tau) + E_i/k_B T] + constant/T \tag{1}$$

where Y is Young's modulus, N is the concentration of defects, k_B, is Boltzmann's constant and A is a constant that depends on the material. The damping factor then depends on temperature in a number of distinct ways, explicitly in the reciprocal in the first term and through the activation energy in the relaxation rate. It was found that the form of equation 1 captures extremely well the functional dependence on temperature exhibited by the three oxides. (Report #3). The equation also provides another insight, namely the dependence of the damping peak temperature, T_p. From examination of the form of equation 1, the damping peak occurs when the term inside the *sech* has a zero value, namely

$$T_P = \frac{E_i}{k_B |\ln \omega \tau|} \quad (2)$$

Although the analysis is based on a dilute concentration of defects whereas the concentration of defects in the oxides we have studied is of the order of tens of percent, it has a number of dependencies that can be correlated with other properties. For instance, the dependence of damping on a high concentration of defects is consistent with the requirement for producing low thermal conductivity by phonon-defect scattering. Similarly, the dependence on low activation energy for diffusional hopping from one site to another is consistent with an oxide having high ionic mobility and hence conductivity. More rigorous evaluation on a larger number of oxides is needed before the analysis can be demonstrated to be a robust guide to other oxides with high damping capacity but it is concluded that a search criteria for identifying oxides with high damping is that they are defect crystal structures and have both high ionic conductivity and low thermal conductivity.

Our studies of the damping properties of defective oxides are significant for two reasons. The first is that these new oxides, although they do not exhibit damping at temperatures of most interest for turbine blades, do offer the possibility of conferring damping to compressor blades at intermediate temperatures. Potentially, these are competitive with the spinel coatings being developed for compressor blades by Rolls Royce. They can be deposited by EB-PVD. The second is that the approach of selecting candidate materials based on defective oxide crystal structures seems to be a promising direction for identifying candidate coating materials for vibration damping.

Damping mechanisms in metals is a well understood subject unlike damping in oxides. The principal mechanisms that have been identified include ferro-elastic damping and magneto-elastic damping. The former is associated with the dissipation that occurs when a boundary, such as a martensite plate or twin, moves in response to an applied stress. The latter is usually associated with changes in the magnetic behavior with strain, strictly a magneto-strictive effect, below the Curie temperature. As the majority of magnetic metals have poor oxidation behavior at high temperatures and the Curie

temperature of most metals is relatively low, our activities were concentrated on higher temperature martensitic metals that have good oxidation resistance.

The platinum-modified nickel aluminides have superior oxidation resistance and as has been demonstrated by Gleeson and colleagues under a separate ONR program have the potential of being modified to be closer to chemical equilibrium with existing superalloys than those currently used as bond-coats. Also, depending on the platinum content, the nickel aluminide alloys can exhibit several martensitic transformations and which occur at different temperatures. Our studies indicate of these alloys indicate rather complex behavior with the damping capacity depending on the platinum content as well as on the thermal history. (Report #4). For instance, in studying the flexural damping characteristics at 1-10 kHz of two Ni-37Al-5Pt and Ni-37Al-10 Pt alloys up to 1150°C correlations were established with martensitic transformations in the alloys determined by means of differential scanning calorimetry (DSC) and optical microscopy. The elastic and damping properties of the alloys are highly dependent of the Pt content as well as on the thermal history. Both alloys exhibit pronounced damping at ~ 900°C. This was attributed to the diffusional transformation of the martensite phase to the high-temperature B2 phase but neither shows any damping on cooling through the transformation to the martensite phase which would be expected of an elastic martensite. Thus, the martensite transformation is not a thermo-elastic martensite and cannot be used to provide damping to flexural vibrations. Rather, it is an isothermal martensite, a conclusion also reached by Gleeson and colleagues. However, a third alloy, containing a lower concentration of Pt (5 a/o Pt) not only undergoes the martensite transformations that occur in the higher Pt alloys studied but also exhibits damping between room temperature and ~ 200°C, the Af temperature determined from DSC studies. Microscopy of this alloy also reveals it has the characteristic plate martensite structure. This lower temperature martensite is thermoelastic and the damping is attributed to vibrational stress induced motion of transformation interfaces as more traditional martensites do. These studies indicate that while there is considerable potential to develop metallic coatings that can function simultaneously as oxidation-resistant and damping coatings, the optimum composition has yet to be identified. Furthermore, as detailed in Reports #5-9, which describe

supporting activities in understanding further aspects of the high-temperature, cyclic oxidation of platinum-modified nickel-aluminide coatings, the cyclic oxidation behavior of this class of alloys can be quite complex.

In summary, during the course of this research program we have: (i) developed a capability of measuring the flexural damping characteristics of materials up to 1200°C in air in the frequency range of interest to gas turbine engines, (ii) identified oxides that exhibit damping at high temperatures and developed a model to predict the temperature at which the damping is a maximum, and (iii) contributed to the development of nickel-aluminide based alloys that can provide both oxidation resistance and flexural damping. In addition, the post-doctoral associate primarily involved in the research is now working in similar areas at Oak Ridge National Laboratory. The instrument for making damping measurements remains intact and is available for use in future DOD or industry programs.

REPORTS OF WORK SUPPORTED UNDER CONTRACT N00014-04-1-0053

Report 1. **Damping of Superalloys and Thermal Barrier Coatings at High Temperatures**, G. Gregori, Li Li, J. A. Nychka and D. R. Clarke, **Vibration** Materials Science and Engineering A, **466** 256-264 (2007).

Report 2. **High- Temperature Vibration Damping of Thermal Barrier Coating Materials**, A. M. Limarga, T. L. Duong, G. Gregori and D. R. Clarke, Surface and Coatings Technology, **202** 693-697 (2007).

Report 3. **Oxides for High Temperature Vibration Damping of Turbine Coatings**, D. R. Clarke, Proceedings of the American Ceramic Society, In press, 2009.

Report 4. **Flexural Vibration Damping and Martensitic Transformations in Pt-Containing Nickel Aluminides**, S. Dryepondt, B. M. Gleason and D. R. Clarke, submitted, 2009.

Report 5. **Temperature and Cycle-Time Dependence of Rumpling in Platinum-Modified Diffusion Aluminide Coatings**, V. K. Tolpygo and D. R. Clarke, Scripta Materialia, **57** 563-566 (2007).

Report 6. **Rumpling of CVD (Ni,Pt)Al Diffusion Coatings Under Intermediate Temperature Cycling**, V. K. Tolpygo and D. R. Clarke, Surface and Coatings Technology, **203** 3278-3285 (2009).

Report 7. **Cyclic Oxidation Induced Cracking of Platinum Modified Nickel Aluminide Coatings**, S. Dryepondt and D. R. Clarke, Scripta Materialia, **60** 917-920 (2009).

Report 8. **On the Initiation of Cyclic Oxidation-Induced Rumpling of Platinum-Modified Nickel Aluminide Coatings**, S. Dryepondt, J. Porter and D. R. Clarke, Acta Materialia, **57** 1717-1723 (2009)

Report 9. **Effect of Superimposed Uniaxial Stress on Rumpling of Platinum-Modified Nickel Aluminide Coatings**, S. Dryepondt and D. R. Clarke, Acta Materialia, **57** 2321-2327 (2009).